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VARIABLES FOR MONITORING AQUATIC AND TERRESTRIAL ENVIRONMENTS

by

Brent M. Graves
Department of Zoology and Physiology
University of Wyoming
Laramie, WY 82071

and

Phillip L. Dittberner
Natural Resource Professionals
1616 Independence Court
Fort Collins, CO 80526

Project Officer

Carl L. Armour
National Ecology Center
U.S. Fish and Wildlife Service
2627 Redwing Road
Fort Collins, CO 80526-2899

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U.S. Department of the Interior
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INTRODUCTION

PURPOSE

In 1983, the U.S. Fish and Wildlife Service published a manual describing statistical procedures, study design, and important variables for monitoring small salmonid streams in the West (Armour et al. 1983). Written primarily for field workers who design and conduct such projects, the manual discussed evaluation of effects due to land management practices, and data analysis. The present report is a supplement to the above publication for terrestrial and aquatic habitats. Users of this manual are referred to Armour et al. (1983) for discussions of basic statistical procedures, planning considerations, and study design concepts.

This manual provides general conceptual guidelines for designing habitat monitoring projects and identifying key variables that may indicate habitat quality. Another purpose is to provide references leading to more detailed discussions of important topics. The field of habitat monitoring is quite broad and appropriate field methods may vary from site-to-site. Hence, this manual cannot provide a step-by-step procedure for habitat monitoring. Rather, it provides a framework and general principles; designers of individual monitoring programs must integrate and adapt these to fit specific circumstances.

Habitat variables in this manual are categorized according to their importance within four ecological types: rivers, lakes, wetlands, and terrestrial habitats. Because of site-specific characteristics, each variable listed may not be important to overall habitat quality in each site observed. Similarly, a variable may be important in ecosystems other than those for which it is listed here. Hence, as in most ecological studies, common sense, basic ecological knowledge, and technical experience are the most valuable commodities in developing study design (Canter and Hill 1979).

RATIONALE FOR DESIGN OF HABITAT MONITORING PROJECTS

Planning

The first step in any environmental monitoring project must involve clear definition of the project's intended goals and how these are to be accomplished. Failure to realize project goals can often be traced back to poor definition of goals and planning procedures. A common fault of many ecological monitoring programs is a tendency to become ends in themselves, rather than careful studies designed to influence management and development of natural areas or to solve problems. As stated by Buffington and Little (1980:197) "It often appears that a lot of answers have been amassed without any advance attempt to formulate relevant questions." The planning stage should specify not only what information is to be acquired, but also the form of such information and what is to be done with it. For example, if results of a monitoring program are to be used by wildlife biologists, they will necessarily be of different substance and format than results to be used by politicians or city planners. Presentation of results is especially important because results presented in an inconvenient format will likely be reinterpreted by someone without expertise in habitat monitoring who is unfamiliar with the specific project. Such a situation presents vast opportunities for confusion and misinterpretation.

Planning should also involve organization of the project into components, with deadlines and a clear delineation of responsibility established for each component. During the planning stage, necessary staff can be organized to meet the requirements of each component. For example, a lawyer may be required to assess legal requirements for the project, taxonomists may be needed to survey species diversity, and biologists or ecologists to collect field data. It is critical that each staff member be familiar with his or her responsibilities and that each task be assigned to the proper staff member.

The intensity or resolution of the study must also be defined. In other words, how accurate must the study be to provide the required information in a usable form? Must every species of plant and animal be cataloged and its density determined or will only the most valuable species or indicator species be examined? When estimating environmental parameters, what will be acceptable confidence intervals? These decisions must be based on the intended uses of the data obtained and or the availability of resources for acquiring data.

The following major phases for an environmental monitoring project have been adapted from those proposed by States et al. (1978).

1. Determine objectives. It is impossible to satisfactorily fulfill the objectives of a study until one has determined what those objectives are. After the objectives of the project have been identified, information and methods to achieve them can be specified.

2. Review existing literature. A literature review can prevent redundancy and provide information for shaping the monitoring protocol. Time and money can be saved by using information obtained by others rather than obtaining data for each new project.

3. Compile a detailed ecological inventory of the area to be monitored. This phase is the core of the baseline study of an ecological monitoring project. The detailed ecologial inventory established at the start of a monitoring project gives one a basis with which future conditions can be compared. Under controlled conditions, changes in habitat quality might be attributed to specific changes in land-use practices.

4. Establish statistically valid baseline measurements. Sampling methods should be chosen based on a number of considerations including accuracy, efficiency, cost effectiveness, and availability of statistical methods for analysis of data obtained.

5. Preliminary development of monitoring programs. After the area has been characterized ecologically, a plan can be developed for monitoring the area during the course of the project. Details of variables to be measured, temporal and spacial aspects of a sampling regimen, and methods of data collection should be considered.

6. Basic research into the response of natural systems to measured perturbations. This work provides insight into probable effects of changes in land use and management. Data gathered under controlled experimental situations can be used to corroborate the assumption that changes in habitat quality result from changes in land use and management.

7. Environmental monitoring during management or use of area. In this data gathering stage of the monitoring process, conditions within the study area are assessed at intervals to determine responses of the habitat to land-use practices. This phase employs information obtained in earlier phases and produces information for analysis and decision making in future phases.

8. Environmental monitoring of area after management program or use of area has been terminated. This is essentially a continuation of step seven. It may provide information on the rate and ability of the system to recover from perturbations and on long-term effects of the land-use system.

Precise planning under each phase allows environmental monitoring to proceed in an organized and timely manner. As in any sequential process, the quality of successive steps is dependent on the quality of previous steps. Each phase should be meticulously planned and its results assessed before those results are used in subsequent phases.

Baseline Studies

States et al. (1978) provide an excellent discussion of development and implementation of ecological baseline studies. They present a seven-step process for baseline studies of ecological parameters, with a chapter devoted to each step. Brief descriptions of the steps are provided here.

Step 1 - Define the decisionmaking framework. Any habitat management project will be defined by a unique set of goals that will be influenced by each of a number of parties involved in the process. The effectiveness of an ecological monitoring program will be dependent on early involvement of all pertinent parties in the identification of information needs and effective methods for obtaining the necessary information.

Step 2 - Compile information base. Completion of a literature review before beginning ecological studies to obtain site specific information will increase efficiency. Previous studies may provide habitat characterizations or data describing environmental responses to various perturbations. Use of existing information can save time and money. Previous studies may also provide historical data that can be useful for studying variations in habitat quality associated with various land-use and management practices. Similarly, it is hoped that results of monitoring projects will be made available to other researchers. Oftentimes, projects of an entrepreneurial nature collect vast volumes of baseline data, which are often not available to others because of their being considered proprietary information. Where there is a Government permitting process involved, however, the baseline data are usually public information and thus available to other people.

Step 3 - Develop conceptual model. A conceptual model is basically an organized compilation of information describing the ecological systems within the area under study. This model can help determine what environmental variables should be measured and can be used after the management or use program to assess impacts. When assessing impacts, the habitat manager should search for cause-effect relationships. A concurrent change in variable levels and habitat quality or population density is merely an association. And, although it is impossible to prove cause-effect relationships, replication of conditions and results can provide some statistical level of assurance that a process is indeed the cause of such a relationship.

Step 4 - Select ecological attributes for study. Environmental variables within a system are virtually infinite; hence, some subset of these must be chosen for monitoring. The selection process is simplified by following the axiom: "monitor what is important," importance being defined by four considerations. First, variables should be ranked based on their relationship to socioeconomic and legal requirements identified in the decision-making framework. Second, a variable's interrelationships in an interdependent network of variables within the ecosystem may influence its importance. Third, variables that are expected to be affected by the management procedures are more important to monitoring projects than variables that are not expected to be impacted. And fourth, variables about which information is already available are less critical to monitor because it may be possible to predict accurately the response of these variables to management while monitoring less well-known variables. After variables are categorized according to importance, a decision must be made concerning which variables are to be monitored and the intensity of monitoring, given the available level of resources. Of course, it is useless to choose variables to be monitored if feasible methods for quantification are unavailable.

Step 5 - Select applicable methods. Methods for quantifying variables should be chosen on the basis of the quality (i.e., accuracy and precision) of data desired and costs involved in applying the method. Quantification methods are described or appropriate citations are given for each variable presented in this manual.

Step 6 - Organize and conduct the field portion of the baseline study. This phase involves implementation of the procedures developed in previous steps. It may be useful to break the collection of baseline data into subprojects in order to more finely structure deadlines and evaluate results throughout the data collection process, not only at finalization. This approach facilitates modification of procedures when inadequacies are first realized, and before these inadequacies can compound their effects by adversely influencing subsequent subprojects. In doing this, care must be taken not to fractionalize the overall project and risk a failure to accomplish the project objectives.

Step 7 - Interpret results for decision-makers. After acquisition and organization into a usable form, ecological baseline data for an area provide a reference against which changes associated with management and use projects can be compared. Adequate baseline data also make it possible to design more reliable projects that maximize beneficial effects (such as increases in population numbers or area of some habitat type) and minimize detrimental effects (such as destruction of critical habitats or changes in physical and chemical attributes of a site). Nonbiologists frequently make project decisions that affect habitat quality. Therefore, baseline information stating conditions and likely outcomes of proposed actions should be condensed, integrated, and presented in a way that ensures that the environmental consequences of the proposed action are understood by everyone involved in the decision-making process.

The above is a brief and general outline for designing and carrying out environmental baseline studies. A more detailed consideration of this subject is presented by States et al. (1978). Although their discussion focuses on baseline studies in preparation for energy development projects in the western United States, the rationale can be applied to baseline studies in any environmental monitoring project. Marmelstein (1978) also provides a wealth of information regarding inventory and classification of fish and wildlife habitat. Radford (1978) provides a useful system for classification and inventory of natural areas.

Monitoring

Monitoring and development of an inventory are not synonymous. An inventory is a listing and quantification of environmental characteristics. Monitoring is the collection and interpretation of population or habitat data to evaluate progress toward meeting objectives, and to indicate needed adjustments. Thus, the important distinction lies in the feedback aspects of monitoring to indicate attainment of goals or needed adjustments (Salwasser et al. 1983).

Buffington (1980) stated that environmental monitoring is not an end in itself. It is only a means for providing data and analytical information for other functions. These functions include environmental policy and management decisions, identification and definition of environmental problems, and evaluation of changes in environmental quality. Monitoring is the process by which ramifications of some land use are quantified and resultant information (feedback) is used to adjust the land-use process to more closely produce desired results.

It is assumed that environmental perturbations directly affect habitat quality, which, in turn, directly affects populations of organisms and community dynamics. Any of the three units of this conceptual and functional chain of events can be assessed and inferences drawn concerning the effects of one unit on successive links or the state of previous links. For example, much of the current monitoring effort seems to focus on the levels and distribution of contaminants, rather than on the end ecological result (Hirsch 1980). In this regard, Cross (1974) discusses monitoring of air pollution, water pollution, noise pollution, pesticide contamination, weather perturbations, radioactivity, and industrial contaminants. These categories measure physical and chemical changes in the environment, which must be interpreted with regard to their possible effects on habitat quality. Another approach is that of biomonitoring as advocated by Cairns (1979). Cairns assumes that the status of key organisms and community structure and dynamics can be assessed and that this data can be used to infer the presence of various environmental perturbations. For the purposes of this manual, either biomonitoring or physical and chemical assessment techniques can be used and estimates of variable values can be interpreted to predict their effects on habitat quality.

Monitoring can also be used to infer effects of land-use practices on habitat quality. Correlation between a land-use practice and changes in habitat quality, however, does not necessarily indicate a cause-effect relationship. Cause and effect can only be inferred by comparing data from disturbed (operational) and undisturbed (control) sites with data collected during baseline studies prior to implementation of the land-use practice (Moore and Mills 1977). Environmental monitoring, as in baseline studies, should be tailored to gathering the type of information pertinent to the questions to be answered.

As in the design and implementation of baseline studies, monitoring programs should be thoroughly planned and executed to provide appropriate information. Moore and Mills (1977) present more detailed guidelines for structuring and carrying out environmental monitoring programs. Overton (1978) discusses design considerations in environmental monitoring. It is especially important during planning stages to ensure that the monitoring project is objectively designed. Green (1979) and Cochran (1977) provide detailed texts concerning sampling theory and statistical procedures for assuring objectivity.

When important species have been identified, whose habitat requirements are to be monitored, the Habitat Evaluation Procedures (HEP) developed by the U.S. Fish and Wildlife Service (Farmer 1978; Cole and Smith 1983) can be helpful in pointing out critical habitat variables and relationships between variables and habitat quality. HEP is a comprehensive, and usable system for monitoring habitat quality. Individual habitat suitability index (HSI) models are designed for assessing habitat quality for single species. HEP provides information that can be used to predict effects of environmental changes on fish and wildlife populations. Habitat Suitability Index models usually concentrate on a few critical environmental parameters that are associated with habitat quality, rather than attempting to monitor actual population changes of the species of interest. Information assembled for use in HSI models, however, can be integrated for use in other situations as well. For example, habitat quality can be monitored for guilds or groups of species that respond in similar ways to changes in a shared habitat type (Short 1983).

A common complaint by authors concerned with the overall direction of environmental monitoring is that data are too often collected simply for the sake of collecting data and then stored, rather than analyzed, integrated, and used in planning and interpreting future studies (Buffington and Little 1980;

Hirsch 1980). A thorough literature review and inquiries made within various agencies may help in avoiding monitoring pitfalls encountered in similar studies, and in interpreting results (Burgess and Stewart 1980).

Prediction

Data are gathered through literature reviews and baseline and monitoring studies to aid in predicting future events within an ecological system. Thus, prediction is the overall goal of the monitoring process. Prediction must be based on observed correlations between environmental characteristics and the values being considered in the project. Cause and effect are difficult to establish in natural systems, however, strong correlations between events and processes observed in numerous unrelated incidences indicate a high probability of a functional relationship. Accurate predictions concerning impacts of changing environmental characteristics using data obtained from a single monitoring project would be very difficult to make. Possible impacts in the situation being studied should be based on observed consequences of similar situations. Predictions should be based on this strong inference (Platt 1964), and the rationale behind predictions should be thoroughly documented. Documentation restricts the use of unsubstantiated opinions and forces those involved to formalize and organize the prediction process.

Recent developments in statistical theory and computer applications have provided new tools for the wildlife manager for characterizing habitat relationships and predicting effects of habitat alteration. Multivariate analysis is especially useful in this regard (Shugart 1981). Multivariate analysis encompasses discriminant function analysis (Klecka 1982), factor analysis (Kim and Mueller 1982a,b), principal component analysis (Totsuoka 1971), canonical correlation (Levine 1982), and multidimensional scaling (Kruskal and Wish 1983). Capen (1981) provides an overview of theory and application of multivariate analysis in the study of habitat.

HEP can also be used for predicting effects on habitat quality due to environmental perturbations. In instances where computer access, statistical expertise, and voluminous data are not available, HEP will be preferable because of its ease of use. Terrell et al. (1982) discuss prediction of future habitat quality conditions at length, using HEP methodology as well as other modeling procedures.

Table 1 presents a matrix relating habitat variables, discussed in this chapter, that land-use practices can affect. Variations in habitat quality are, of course, much more complex than this presentation indicates. Most habitat variables covary with one another and influences are interrelated. Hence, virtually every land use listed in the table can in some way affect each environmental variable. This table summarizes the most common and direct influences. For example turbidity can be affected by several land-use practices including construction projects and dredging.

Table 1. Summary table of aquatic variables discussed and land-use practices that may affect each variable.

Variables	Actions Affecting Aquatic Variables															
Aquatic	Construction projects	Dredging	Waste discharges	Impoundments	Industiral/municipal water consumption	Irrigation	Drainage	Erosion	Livestock grazing	Acid rain	Vegetation removal	Water velocity changes	Solar penetration	Species introductions	Fires	Floods
Turbidity	X	X	X	X				X	X			X		X		X
Water level fluctuations	X		X	X	X	X	X					X				X
Total dissolved solids			X					X	X		X					X
pH			X					X		X						
Depth		X		X	X	X	X	X								X
Shoreline vegetation	X			X			X		X		X				X	X
Submergent and emergent vegetation	X	X	X		X			X	X	X	X	X	X	X	X	X
Salinity	X		X													
Dissolved oxygen concentration		X										X				
Temperature		X	X	X								X	X			X
Substrate composition	X	X	X	X				X	X		X					X
Biochemical oxygen demand			X					X	X		X					
Plankton abundance and diversity	X	X	X	X	X	X	X			X		X	X			
Benthos abundance and diversity		X	X	X			X	X	X	X	X	X	X	X		
Current velocity	X	X	X	X	X	X	X	X			X	X				X
Width	X	X	X	X	X	X	X	X			X	X				X
Pool/riffle	X	X	X	X	X	X	X	X			X	X				X
Sinuosity	X	X		X		X	X	X				X				X
Instream flow	X	X	X	X	X	X	X									X
Trophic class	X	X	X		X	X	X	X	X	X	X		X			
Shoreline development factor		X						X			X					X
Surface area		X	X		X	X	X	X								X
Littoral area	X	X			X	X	X	X			X		X			X
Storage ratio and flushing rate		X			X	X	X					X				X
Area Flooded annually	X	X	X	X	X	X	X	X			X					X
% of year flooded	X	X	X	X	X	X	X	X			X					X
% open water area		X		X	X	X	X	X			X		X	X		X
Forest cover		X		X				X	X		X			X		X
Vegetative heterogeneity	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

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LAND-USE IMPACTS AND MONITORING VARIABLES FOR AQUATIC HABITATS

Table 2 lists variables commonly measured for monitoring aquatic habitat quality. Listed first are general variables that apply to any of the three aquatic habitat types (i.e., riverine, lacustrine, and palustrine; Cowardin et al. 1979). The next three columns list important variables specific to each habitat type. General variables are discussed first, with variables relating specifically to riverine, palustrine, and lacustrine habitats discussed under separate headings.

GENERALLY APPLICABLE AQUATIC HABITAT VARIABLES

Turbidity

Turbidity describes the extent to which light is scattered by suspended and colloidal material as it passes through a water column. The most direct effect of turbidity is that it restricts the depth to which solar radiation can penetrate, and consequently, to which photosynthesis can occur. Additionally, turbidity may be indicative of several factors affecting habitat quality. For example, turbid waters generally have very fine substrate compositions and high erosion from the drainage area. While some water is naturally turbid, construction projects, dredging, and waste discharges can increase turbidity, whereas impoundments can decrease turbidity due to settling of suspended particles. Habitat quality for many fish species has been associated with various turbidity levels [e.g., largemouth bass (Micropterus salmoides) (Stuber et al. 1982a); black bullhead (Ictalurus melas) (Stuber 1982); common carp (Cyprinus carpio) (Edwards and Twomey 1982a)].

Turbidity is generally expressed in Jackson Turbidity Units (JTU) where one JTU is equal to the turbidity caused by 1 mg/ℓ of SiO_2 in water. Turbidity was previously quantified using a Jackson candle but has been replaced by the nephelometer, which measures the light scattered at a 90° angle. Alternatively, a spectrophotometer can be used to quantify the amount of light that is transmitted, which is approximately inversely related to the amount of light scattered. Methods for use of the above techniques are described in Lind (1979).

Water-Level Fluctuations

Frequency and magnitude of water-level fluctuations affect habitat quality by flooding or exposing breeding areas or habitat for young (Benson 1973; Miracle and Gardner 1980; Inskip 1982; Stuber et al. 1982a,b). Increases in water level often are associated with increases in current velocity and turbidity, with consequent siltation. Decreases in water level remove aquatic habitat from use and dessicate littoral zone vegetation. Water fluctuations resulting from land-use practices are usually the product of dams, industrial and municipal consumption, irrigation, and drainage projects. Data should be

Table 2. Commonly measured aquatic habitat variables.

General aquatic variables	Riverine variables	Lacustrine variables	Palustrine variables
Turbidity	Current velocity	Trophic class	Area flooded annually
Water-level fluctuations	Width	Shoreline development factor	Percent of year flooded
Total dissolved solids	Pool/riffle ratio	Surface area	Percent open water area
pH	Sinuosity	Littoral area	Forest cover
Depth	Instream flow	Storage ratio and flushing rate	Vegetative heterogeneity
Shoreline vegetation			Vegetative heterogeneity
Submergent and emergent vegetation			
Salinity			
Dissolved oxygen concentration			
Temperature			
Substrate composition			
Biochemical oxygen demand			
Plankton abundance and diversity			
Benthos abundance and diversity			

gathered by measuring water depth or waterline level at a specified point on the shoreline on a specified time schedule.

Total Dissolved Solids

Total dissolved solids (TDS) are the aggregate of carbonates, bicarbonates, chlorides, sulfates, phosphates, nitrates, and other salts of calcium, magnesium, sodium, potassium, and other substances (Canter and Hill 1979). Waters with excessively high levels of TDS are unsuitable as habitat for some species because of ionic balance and other physiological effects caused by mineral content levels (Jenkins 1976; Finnell 1979). Some of the above compounds can also affect pH. Human-related activities are usually responsible for increases in TDS. For example, runoff from fertilized land, inadequate sewage systems, increases in topsoil erosion, and heavy livestock concentrations can increase TDS in waters.

Total dissolved solids in a water sample can be determined by evaporating a measured amount of sample from a preweighed container at 103 °C. The container should be dryed in a dessicator before and after evaporation. The TDS of a sample is determined by subtracting the original weight of the container from the final weight and dividing by the volume of the sample. This value is then expressed as mg TDS per liter (Lind 1979).

pH

Hydrogen ion concentration is expressed as pH ranging from 0 (very acidic) through 7 (neutral) to 14 (very basic). The pH level has major effects on physiological reactions and membrane characteristics (Schmidt-Nielsen 1979). Upper and lower pH limits vary among fish species, but young and eggs are usually the most affected (McCarraher 1962). Runoff that passes through mine tailings or other industrial waste can have major effects on pH when entering natural waters (Moore and Mills 1977). Acid rain resulting from airborne sulfur dioxide emissions has drastically affected habitat quality in many natural waters (D'Itri 1982).

pH is easily measured using pH paper, or more accurate determinations can be made using a pH meter (Lind 1979).

Depth

The depth of water in a particular area interacts with and affects many habitat variables. Deep water is often stratified thermally, which affects dissolved oxygen content in the various layers. Many emergent and submerged vegetation types can grow only in certain water depths. Many animals lay eggs in shallow water but feed in deeper water, and utilize varying depths as water temperatures change seasonally. Water depth of lotic habitats affects current velocity and the distribution of pools and riffles. As with many habitat variables, a strong correlation exists between specific levels of the variable and population densities for specific taxa. For example, longnosed dace (*Rhinichthys cataractae*) are most often found in water between 0.2 and 0.8 meters deep (Edwards et al. 1983), whereas creek chub (*Erimyzon oblongus*) are most often found between 0.5 and 1.0 meters (McMahon 1982). Changes in water depth are usually due to dredging, damming, and removal or addition of water as in irrigation and drainage.

Depth is most easily measured by dropping a weighted chain, marked in appropriate units, to the bottom. Hays et al. (1981) suggest the use of a graduated rod to insure an accurate vertical measurement. Mean depth can be calculated by dividing the volume of the water body by the surface area. Volume can be determined by planimetric integration or summing the volume of conical segments (frustra), with upper and lower surfaces delimited by sequential depth contours (Lind 1979). Techniques for measuring depth are also discussed in Armour et al. (1983).

Shoreline Vegetation

Shoreline vegetation has three primary effects on habitat quality: (1) it stabilizes banks, which reduces erosion; (2) it provides shade and thus reduces photosynthesis rates and temperatures; and (3) it introduces allochthonous organic matter into the aquatic habitat, which provides food, increases biological oxygen demand, dissolved solids and suspended solids, and changes the substrate composition. Also, trees that fall into the water provide cover, basking, and breeding sites for certain animals. Shoreline vegetation provides habitat for organisms consumed by aquatic species (Hynes 1970).

Shoreline cover may be calculated in proportion to shoreline length having vegetation of some type (e.g., conifer, deciduous, grass, shrubs), species, or size (above and below some height). These data may be expressed as length of shoreline having the vegetation of interest per total shoreline length, percent canopy cover, or frequency of some type of vegetation per length of shoreline (McMahon 1982, 1983).

Submergent and Emergent Vegetation

This class of vegetation includes all plants growing within the boundaries of the water body. Submergent vegetation does not protrude above the water surface; emergent vegetation does. Vegetation is important primarily for food and cover for aquatic species. Herbivorous terrestrial animals also sometimes feed on both submergent and emergent vegetation and also provide prey for animals further along the trophic network. Aquatic vegetation density is affected by the species present (e.g., carp and snapping turtles eat large amounts of vegetation), nutrients in the water, substrate composition, and solar penetration. Vegetation can be quantified as species present per cubic meter, percent of surface area with some density of vegetation, or biomass of vegetation per unit area.

Salinity

Salinity affects habitat quality through the ability or inability of various species to maintain osmotic balance in waters with a specific salt content. Salinity is defined as the total solids in water after all carbonates have been converted to oxides, all bromides and iodides have been replaced by chlorides, and all organic matter has been oxidized (Canter and Hill 1979).

Salinity is most important and subject to change in coastal and estuarine water bodies, but can be a factor in inland waters, as evidenced by the biotic paucity of the Great Salt Lake in Utah. Connection of freshwater and saltwater bodies, dumping of salt-laden substances, and evaporative concentration can alter salinity. Optimal salinity may change for a single species at different life stages (Pardue 1983), and rate of change in salinity can be important (Diaz 1982) because some species can adapt to various salinities but have a maximal rate of physiological adaptation. Also, salinity can affect behavioral characteristics of species (Cake 1983) and food availability (Christmas et al. 1982). Salinity is often expressed as parts per thousand (ppt) (Edwards et al. 1982c), is not synonymous with total dissolved solids although it is sometimes used as such (Edwards and Twomey 1982b). Procedures for measuring salinity are described in Hamilton and Bergersen (n.d.).

Dissolved Oxygen Concentration

Dissolved oxygen must be of sufficient concentration within waters to enable its diffusion into an animal's blood. Oxygen is a product of photosynthesis and its concentration is thus a function of primary productivity within the aquatic system. Surface layers are generally well oxygenated because of diffusion from the air and strong photic penetration and resultant photosynthesis (Wetzel 1975). Similarly, water with heavy phytoplankton concentrations in upper layers may have much dissolved oxygen in upper layers (due to photosynthesis) but little in lower layers (due to shading effect of dense phytoplankton) (Hutchinson 1938); deeper layers have progressively less dissolved oxygen. Moving water generally has greater dissolved oxygen than standing water due to mixing with air. Different dissolved oxygen levels may be needed by different life stages of fish (McMahon 1983; McMahon et al. 1984), and eggs and fry usually require higher levels than adults. Generally, 3 mg/ℓ dissolved oxygen or less is stressful to aquatic vertebrates (Lind 1979) and concentrations greater than 6 mg/ℓ function biologically as a buffer against short-term dumping of waters with high biological oxygen demand (Canter and Hill 1979). The Winkler method for determination of dissolved oxygen is accurate to ±0.05 mg/ℓ except at low concentrations. Procedures for measuring dissolved oxygen levels are described in Lind (1979) and Brown (1971).

Temperature

Water temperature directly affects, and is usually equivalent to, the body temperature of aquatic organisms. Body temperature influences the rate at which metabolic reactions occur by affecting the reactivity of enzymes. Some organisms can adapt to various temperature regimes by producing isoenzymes (Schmidt-Nielson 1979), but such enzymatic change usually takes some time. Warm water holds less dissolved oxygen than cooler water; oxygen saturation varies from 14.6 mg/ℓ at 0 °C to 5.6 mg/ℓ at 50 °C at one atmosphere of pressure (Brown 1971). Heating of upper levels by solar radiation produces thermal stratification (in summer) in lentic systems, which inhibits mixing of layers. Lakes also stratify (inversely) in winter because water is densest at 4 °C. Therefore, complete mixing occurs only in fall and spring in dimictic lakes, when all water reaches equal temperature (Wetzel 1975). Different species prefer different water temperatures [e.g., longnose sucker (Catastomas catostomas), 12 °C (Edwards 1983a); black bullhead (Ictaluras melas), 18-29 °C

(Stuber 1982); bigmouth buffalo (*Ictiobus cyprinellus*), 30-34 °C (Edwards 1983b)]. Also, different life stages of a single species may require different temperatures (Edwards and Twomey 1982a; Stuber et al. 1982a). Impoundments, depth, vegetative shading, and inputs of water can alter water temperature (Warner et al. 1974). Temperature may be easily measured with a thermometer or thermocouple lowered to the appropriate depth. Other considerations and methods for temperature monitoring are discussed in Armour et al. (1983).

Substrate Composition

Substrate composition is indicative of other general aquatic habitat characteristics. Bedrock or sandy substrates are usually found in oligotrophic waters and are frequently associated with low temperature, great depth, and low productivity. Muddy substrates are frequently found in more eutrophic waters and are associated with the characteristics opposite of those listed for oligotrophic waters. Certain types of substrates are utilized by species for various life history functions, for example, muddy substrates are required for frogs and turtles to burrow into during hibernation (Moyle 1973; Froese 1978). Fish often require certain substrate types for spawning [e.g, black bullhead require fine substrates (Stuber 1982); creek chub (*Erimycon oblongus*) require gravel and bedrock (McMahon 1982); and the common shiner (*Notropis cornutus*) requires an intermediate sand and gravel substrate (Trial et al. 1983)] or for intermediate food production (McMahon 1982). Substrate composition is usually changed from courser to finer particles by increased erosion within the watershed, increased organic input, and settling of suspended solids in the impoundment behind a dam (Warner et al. 1974). This siltation can affect the composition of the aquatic biota. For example, deposition of sandy silt in an Ontario stream after construction of a beaver dam caused a decrease in invertebrates such as caddisflies (Trichoptera), mayflies (Ephemeroptera), and stoneflies (Plecoptera), while taxa of midges (Chironomidae) increased (Hynes 1970).

Substrate type is determined by collecting a representative sample and passing the sample through a series of progressively smaller sieves. The weight of dry material captured in each sieve is divided by the total dry weight of the sample to get the percent of the substrate composed of each size class. Additional measurement techniques are presented in Armour et al. (1983).

Biochemical Oxygen Demand

Biochemical oxygen demand (BOD) is defined as the amount of oxygen (mg/ℓ) required by bacteria while stabilizing decomposable organic matter under aerobic conditions (Canter and Hill 1979). BOD indicates the quantity of biologically degradable organic matter in the water body and so provides information on the trophic status of aquatic habitats. Unless much mixing or photosynthesis occurs, water with high BOD usually has low dissolved oxygen concentration. Sewage or feedlot runoff can increase organic content, which increases the BOD of water. Herbicide treatment of a water body leaves large amounts of dead plant matter, placing a high BOD on the system. Stack (1973) and Canter (1977) provide information useful for calculation of BOD. Biochemical oxygen demand decreases downstream from point sources of organic input. Velz (1970) and Nemerow (1974) describe mathematical models for predicting downstream levels of BOD.

Plankton Abundance and Diversity

Plankton are small organisms that float in water, and whose movements are largely dependent on water movements (Lind 1979). Phytoplankton consists primarily of photosynthetic, free-living bacteria, protists, and algae (Weber 1978), and zooplankton are their heterotrophic counterparts (Sage 1978). Phytoplankton provide much of the primary productivity of an aquatic system and zooplankton make up a large proportion of the primary consumers and food for secondary consumers. Hence, plankton abundance and diversity indicate the productivity and stability of an aquatic habitat (Canter and Hill 1979). Plankton diversity and abundance can vary with the organic, toxic, and solar input to a system, dissolved oxygen concentration, temperature, and season. Thus, plankton serve both as a food source for higher trophic levels and as indicators of environmental conditions.

The zooplankton/phytoplankton dichotomy roughly parallels the net-plankton/nanoplankton division, the latter pass through a 63 µm mesh net, whereas the former do not. Methods for sampling and interpretation of samples are reported in Patrick (1972), Cross (1974), Sage (1978), Weber (1978), and Lind (1979).

Benthos Abundance and Diversity

Benthos also serve as food for higher trophic levels and as indicators of environmental conditions. This class of organisms consists of bottom-dwelling species. Certain species are characteristic of littoral, sublittoral, and profundal zones (Cole 1975). Benthos includes both plants and animals and thus provides food and cover, and habitat for prey species. Changes in benthic community structure are indicative of changes in habitat quality (Gaufen 1973; Isom 1978). Methods for quantification of benthic community structure are described in Lind (1979), Isom (1978), and Cross (1974).

In addition to the above variables dealing with habitat parameters, several variables dealing with parameters of the populations or communities whose habitat quality is under consideration can be quantified. These include species composition and relative abundance (community structure), lengths, weights, population numbers, and biomass. These variables and techniques for quantification are discussed in Armour et al. (1983).

RIVERINE VARIABLES

Rivers are defined here as lotic (flowing) bodies of water, other than trout streams (which were discussed in Armour et al. 1983). When developing a monitoring program it is useful to be aware of land-use practices that can result in changes in habitat variables within a river. Many changes in habitat quality within a river are due to changes in land-use practices along the river, or along one or many of the river's tributaries. Thus, a wide-angle approach must be taken when looking for the causes of changes in river habitat characteristics. Also, which riverine variables are important for assessing whether the goals of a specific management project have been reached, will depend on which species or guilds of species are deemed important.

Mining, grazing, irrigation, dams, deforestation, channelization, and introduction of organic, inorganic, and biological substances into the river by other means can all affect habitat quality (Figure 1). For example, mining projects or timber harvests often involve stripping of vegetation resulting in increased runoff, increased erosion, and greater solar warming. Each of these indirect effects of vegetation removal, in turn, produces or adds to several secondary effects. Consequently, land-use practices may be additive in their effects on some environmental variables. Also, events occuring outside of the river often change characteristics within the river, and affect habitat quality. Impoundments and channelization, on the other hand, directly impact on the river. Impoundments will be treated as lakes in this document, although it should be noted that these modifications to lotic systems result in habitat changes (warming or cooling of water, settling out of suspended materials, and growth of aquatic plants and plankton) downstream from and within the impoundment (Warner et al. 1974).

Current Velocity

Current velocity is the speed at which water travels. Current velocity is not constant throughout a river but varies with depth and width of the water body. It is most greatly affected by the river's gradient (vertical drop per horizontal distance). Thus, channelization can decrease current velocity by increasing depth and can increase current velocity by removing sinuosity, thereby forcing the river to cover less horizontal distance per vertical drop. Removal of vegetation can increase runoff from a river's water-shed, thereby increasing discharge and current velocity. Placement of obstructions in the river channel increases current velocity by effectively narrowing the river's width and forcing the volume of water to pass through a smaller area. Friction from water passing over the substrate slows current velocity, causing water to move slowly along the water substrate interface and more rapidly towards the surface and mid-depth. Thus, current velocity is highly variable along the rivers length and cross-section depending on specific conditions at each point. Because of this variability, current velocities within specific microhabitats may be more important to habitat quality than mean or maximum current velocity within a river (Hynes 1970). Higher current velocity generally results in greater mixing within the water and between water and air, producing higher dissolved oxygen concentrations.

Current velocity is often standardized by taking measurements at 0.6 m depth (Edwards et al. 1982a,b; McMahon 1982; Stuber 1982; Trial et al. 1983). Movement of neutrally-bouyant objects and dyes can be used to measure current velocity, however, current meters are preferable for measuring velocity in specific locations (Welch 1948; Brown 1971; Cross 1974; Lind 1979; Armour et al. 1983). Stalnaker and Arnette (1976) discuss methodologies for assessing streamflow characteristics and impacts of flow alteration on ecological systems.

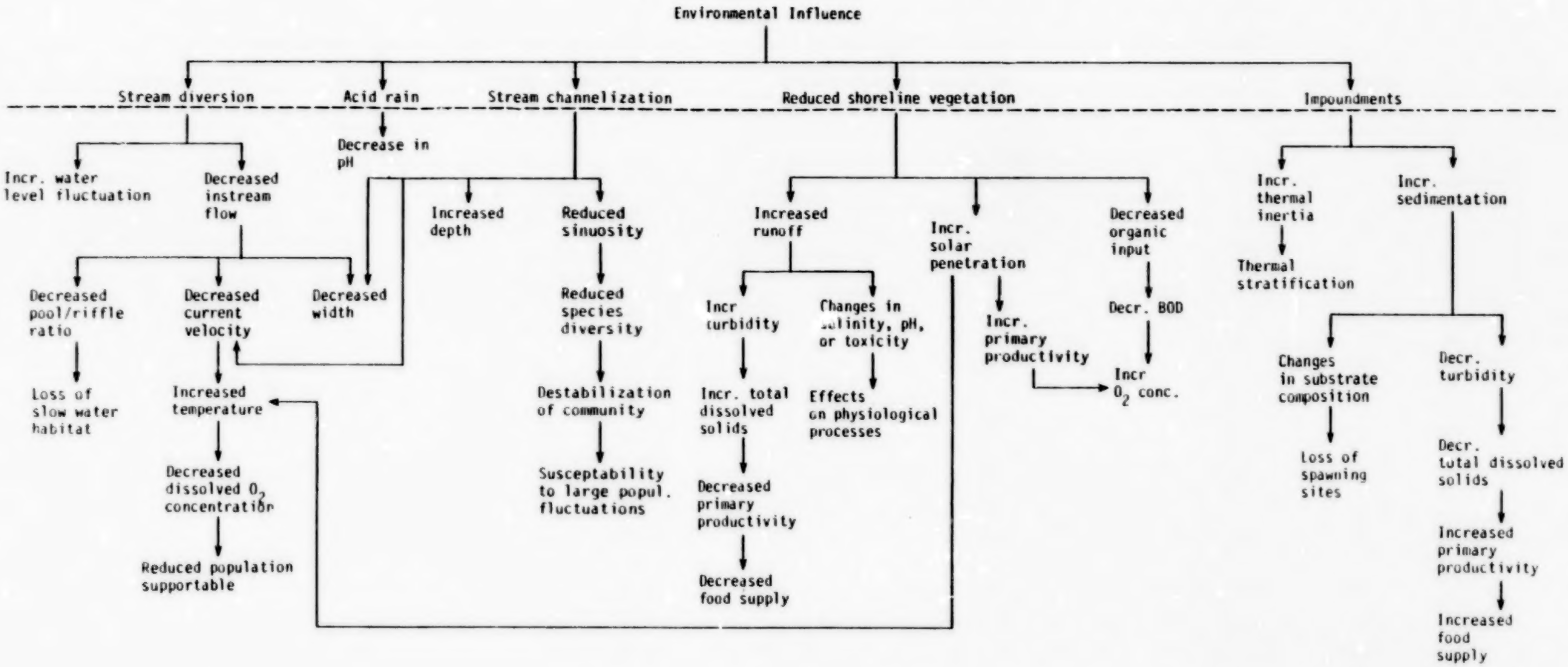
Environmental Influence
Stream diversion
Acid rain
Stream channelization
Reduced shoreline vegetation
Impoundments
Incr. water level fluctuation
Decreased instream flow
Decrease in pH
Increased depth
Reduced sinuosity
Increased runoff
Incr. solar penetration
Decreased organic input
Incr. thermal inertia
Incr. sedimentation
Decreased pool/riffle ratio
Decreased current velocity
Decreased width
Reduced species diversity
Incr turbidity
Changes in salinity, pH, or toxicity
Incr. primary productivity
Decr. BOD
Thermal stratification
Loss of slow water habitat
Increased temperature
Destabilization of community
Incr. total dissolved solids
Effects on physiological processes
Incr O2 conc.
Changes in substrate composition
Decr. turbidity
Decreased dissolved O2 concentration
Susceptability to large popul. fluctuations
Decreased primary productivity
Loss of spawning sites
Decr. total dissolved solids
Reduced population supportable
Decreased food supply
Increased primary productivity
Increased food supply

Figure 1. Potential impacts of diverse land uses on riverine habitat. Above the dashed line are land-use practices and below are some of their effects on environmental variables and habitat quality.

Width

Width of a lotic water body is associated with presence and abundance of many species. For example, creek chub (McMahon 1982) and longnose dace (Trial et al. 1983) are usually found in small streams (<12 m wide), green sunfish (*Lepomis cyanellus*) (Stuber et al. 1982c) are generally found in small to medium streams (<30 m wide), and smallmouth buffalo (*Ictiobus bubulos*) (Edwards and Twomey 1982b) are usually found in medium to large streams (>25 m wide). Changes in river width are often the result of increases or decreases in discharge volume, bank erosion, channelization, or sedimentation.

Width can easily be measured with a tape measure; an optical range finder may be employed for greater distances (Hays et al. 1981). Width will likely vary along a rivers length, but multiple measurements can be averaged to obtain mean width.

Pool/Riffle Ratio

Because current velocity is often highly variable at different points within a lotic water body, it may be more realistic, and a better description of habitat conditions, to quantify the proportions of stream area exhibiting various current velocity characteristics. A commonly used method is to divide the river or stream into pool and riffle sections and to express their relative abundance as a pool to riffle ratio. Riffles are areas having fast water whose surface is broken by submerged structures, whereas pools are deep areas of slower water with smooth surfaces. Methods for quantification of pool/riffle parameters are discussed in Armour et al. (1983).

Sinuosity

Sinuosity is a measurement that describes the degree to which a river or stream deviates from straightness. It is expressed as the ratio of the stream's actual length to the straight line distance between two points along the river. Sinuosity is proposed to indicate habitat diversity within a stream reach (Canter and Hill 1979). Sinuosity may be changed by channelization, impoundments, or increases in stream discharge that break through oxbows.

Instream Flow

The instream flow approach to describing lotic systems relates physical stream variables (e.g., velocity, depth, width, substrate, temperature, and cover) to habitat quality for each major life stage of a given fish species (spawning, egg, incubation, fry, juvenile, and adult). The Instream Flow Incremental Methodology (IFIM) has been developed by the U.S. Fish and Wildlife Service to quantify and interpret these relationships (Bovee 1982). The Physical Habitat Simulation System (PHABSIM) is a component of the IFIM and is described by Milhous et al. (1984). Procedures for measuring stream velocity, volume discharge, and channel structure characteristics are presented in Lind (1979). Instream flow is affected by activities that remove or introduce water to the stream.

LACUSTRINE VARIABLES

Lakes are designated here as nonmarine, lentic (standing water) habitats. Reservoirs are included in this category, although they can be functionally different from lakes in several respects. For example, reservoirs usually receive more organic and silt input than do natural lakes, and thermal stratification of reservoirs can be drastically affected by where, along the dam's vertical depth, water is released (Warner et al. 1974). All of the habitat variables discussed below, however, are suitable for habitat description and quantification in reservoirs as well as lakes, so the two will be grouped here. Major impacts on lake habitats are frequently the result of siltation, input of organic matter through seepage or dumping, or changes in shoreline through removal of vegetation, sand or gravel dumping, bank erosion, and water level changes (Figure 2).

Trophic Class

Trophic class is the broadest habitat classification variable discussed here, but is exceptionally useful in predicting habitat quality for various species. This is because many habitat variables covary with one another. Trophic class generally characterizes the organic productivity of a water body. Very productive waters are called eutrophic, very unproductive waters are oligotrophic, and mesotrophic lakes are somewhere between these two extremes. Bog lakes are termed dystrophic and are characterized by brownish water and low dissolved calcium, pH, and productivity (Wetzel 1975). Eutrophic lakes are usually shallow and warm and have a highly organic substrate and high dissolved nutrient content. Oligotrophic lakes are characterized by opposite levels of the same parameters. Leach et al. (1977) discuss in greater detail parameter levels associated with each trophic class. Certain species are more abundant in certain trophic classes of lakes. For example, walleye (Stizostedion vitreum) and yellow perch (Perca flavescens) (Krieger et al. 1983) are most abundant in mesotrophic lakes, and bullfrogs (Rana catesbeiana) (Moyle 1973) are most abundant in eutrophic lakes. Many other lake classification systems have been devised (Cole 1975), however, trophic classification is the most widely applied in habitat studies. Eutrophication is accelerated by activities that increase primary productivity, such as increased organic input into the lake, increased solar absorption, and increased concentrations of molecules important to plant growth (e.g., phosphates and nitrates).

Shoreline Development Factor

Shoreline development is an index of the regularity of a shoreline. Lakes that form a perfect circle have a shoreline development factor equal to one; higher values indicate irregularity. Shoreline development is associated with the age of a lake. As lakes age, shoreline development theoretically approaches unity due to erosional smoothing of the shoreline. Reservoirs filling numerous side valleys can have high shoreline development factors (Lind 1979). Therefore, shoreline development factors change and are affected by increasing erosion rates, changes in water level, and dredging and filling projects. Shoreline development is determined using the following equation.

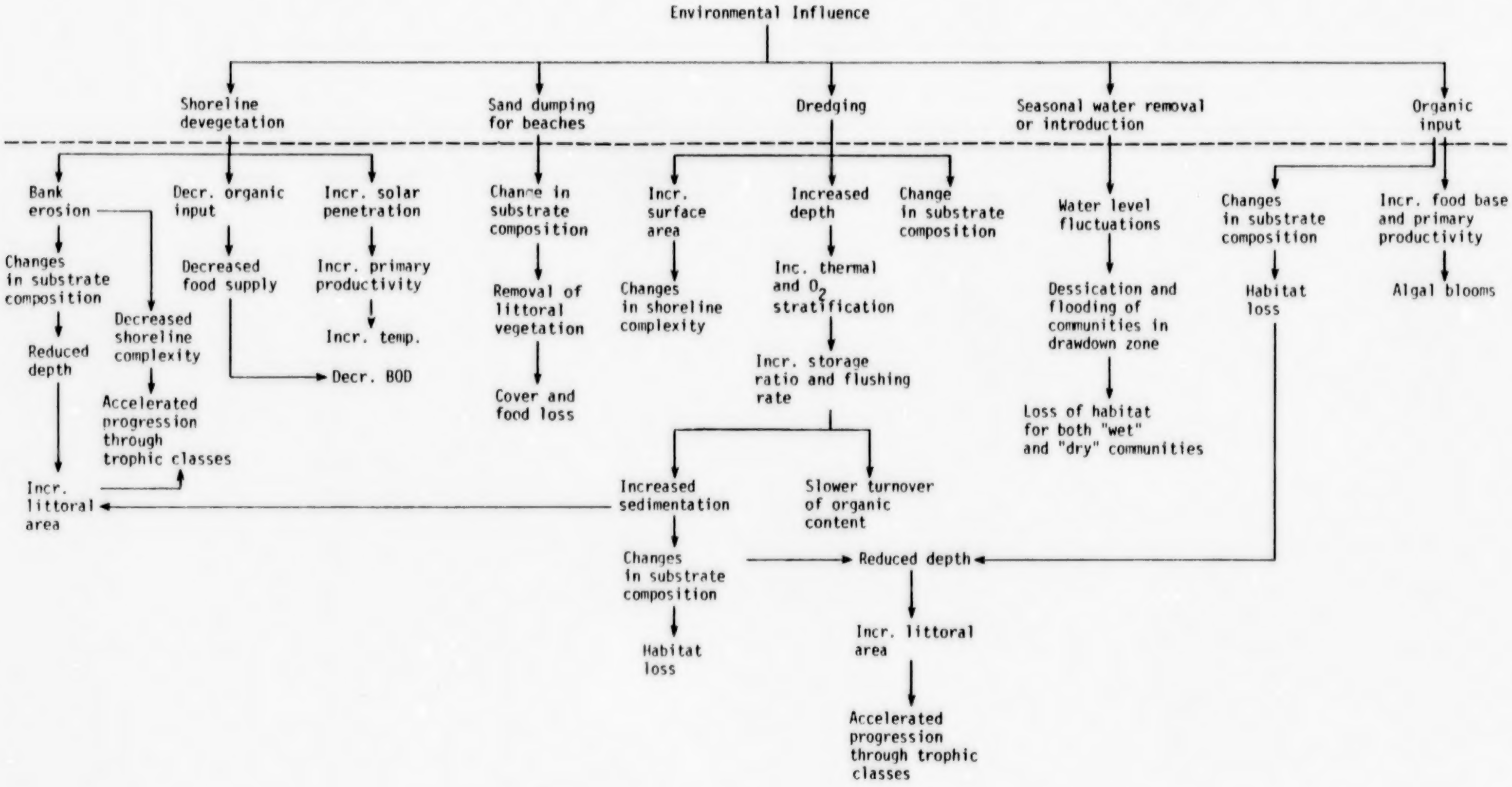
Environmental Influence
Shoreline devegetation
Sand dumping for beaches
Dredging
Seasonal water removal or introduction
Organic input
Bank erosion
Decr. organic input
Incr. solar penetration
Changes in substrate composition
Decreased food supply
Incr. primary productivity
Decreased shoreline complexity
Incr. temp.
Reduced depth
Decr. BOD
Accelerated progression through trophic classes
Incr. littoral area
Change in substrate composition
Removal of littoral vegetation
Cover and food loss
Incr. surface area
Changes in shoreline complexity
Increased depth
Inc. thermal and O_2 stratification
Incr. storage ratio and flushing rate
Change in substrate composition
Increased sedimentation
Slower turnover of organic content
Changes in substrate composition
Habitat loss
Reduced depth
Incr. littoral area
Accelerated progression through trophic classes
Water level fluctuations
Dessication and flooding of communities in drawdown zone
Loss of habitat for both "wet" and "dry" communities
Changes in substrate composition
Habitat loss
Incr. food base and primary productivity
Algal blooms

Figure 2. Potential impacts of diverse land uses on lacustrine habitats. Above the dashed line are land-use practices and below are some of their effects on environmental variables and habitat quality.

$$SLD = \frac{S}{2\sqrt{A\pi}}$$

where SLD = Shoreline development

S = Length of shoreline

A = Area of lake

Surface Area

Surface area of a lake can affect habitat quality in several ways. If a species uses only a certain stratum of water (e.g., within .3 m from the surface) but uses that stratum uniformly, surface area influences habitat availability within a lake. Similarly, given equivalent basin shapes, a lake with a smaller surface area will have a greater percentage of its area in the littoral zone, whereas larger lakes will have a greater percentage of pelagic zone. Black bullhead exhibit greater population densities in smaller lakes due to a greater proportion of shallow-water cover areas (Stuber 1982). Surface area may be changed by drainage, filling, or dredging. Also, two adjacent water bodies might be connected by a channel, effectively combining the two into one unit. Lind (1979) describes polar planimeter and cut and weigh methods for determination of area, but suggests the use of polar planimetry when instrumentation is available.

Littoral Area

Littoral area is defined as the area in which aquatic plants grow (Cole 1975). This habitat is required by many species for cover, food production, (McMahon and Terrell 1982; Stuber 1982; Stuber et al. 1982b; Edwards 1983b) and spawning (Edwards et al. 1982b). Too high a percentage of littoral area can be detrimental to habitat quality because deeper water is needed by certain species for foraging (Edwards and Twomey 1982a,b; Stuber et al. 1982b) and some species forage along the littoral-pelagic boundary (Inskip 1982). Littoral area can be changed by heavy siltation, shoreline erosion, dumping of sand and gravel for beaches, changes in water level, and dredging. Littoral area is best quantified by mapping the water body and making depth and substrate composition measurements.

Storage Ratio and Flushing Rate

Storage ratio and flushing rate are primarily relevant to reservoirs, but can also influence habitat quality in lakes with outflowing streams. Storage ratio is defined as the ratio of volume to the average annual discharge. A more season-specific variable that also relates volume and discharge rate is the flushing rate, which is the time needed for a volume equal to the volume of the lake to be discharged. Both of these variables are important to habitat quality because of their effects on nutrient removal and removal of fry (McMahon and Terrell 1982). Values for these parameters are easily altered in reservoirs by opening and closing flood gates. Also, if water level is held constant but influx increases, discharge will necessarily increase as well. Changes in volume while holding discharge constant similarly alter storage ratio and flushing rate. Lind (1979) describes methods for determining both volume and flow of a lake or reservoir.

PALUSTRINE VARIABLES

Palustrine habitats are highly productive areas that are permanently or seasonally inundated with shallow water (see Cowardin et al. 1979, or Stewart and Kantrud 1971 for descriptions and types). Palustrine environments are especially important as breeding habitat for ducks, semiaquatic mammals such as muskrats (Ondatra zibethica), mink (Mustela vison), and raccoons (Procyon lotor), and other less economically important species. Management practices that can affect habitat quality include dredging, building water level stabilization devices, planting desired species, water drawdowns, ditch construction, animal species introduction, and building nesting structures (Yoakum et al. 1980; Weller 1978). Figure 3 illustrates these environmental influences and the resultant habitat effects.

Area Flooded Annually

Many palustrine habitats are flooded in spring and slowly dry-up as the season progresses. It is useful to know the extent to which an area is flooded at high water. Some species require dry areas and others require wet areas, or temporarily wet areas, and these characteristics can influence habitat quality for various palustrine inhabitants (Canter and Hill 1979). Changes in basin shape, drainage, dredging, diversion of water for irrigation, and various water stabilization measures can alter the area of a habitat that is flooded annually. Area flooded annually may be defined as the average area of a habitat that is covered with water at some time during the year. Methods for estimating this parameter involve taking aerial photographs of the area in question, then laying a grid over the photographs. The number of grid sections covering a flooded area are counted and divided by the total number of grids in the area to get the percent of area flooded (Hays et al. 1981). If flooded areas are fairly regularly shaped, estimates of area may be made by measuring the circumference or width using an optical rangefinder, map measurer, pacing, or tape and converting the measurements to area using appropriate formulae.

Percent of Year Flooded

The proportion of the year that an area is flooded also provides information relative to its quality as habitat. Areas with standing water year round, standing water during spring, or standing water during fall have varying qualities as habitat for different species. Muskrats, for example, require standing water for a greater percentage of the year than do mink (Allen 1984; Allen and Hoffman 1984). Flood duration in an area on a year-to-year basis may be affected by drainage for irrigation, flood control projects, changes in the basin's topography (i.e., dredging, filling), changes in canopy closure (hence changes in shading and evaporation rate), and diversion of water inlets or outlets. The percentage of the year for which an area has standing water

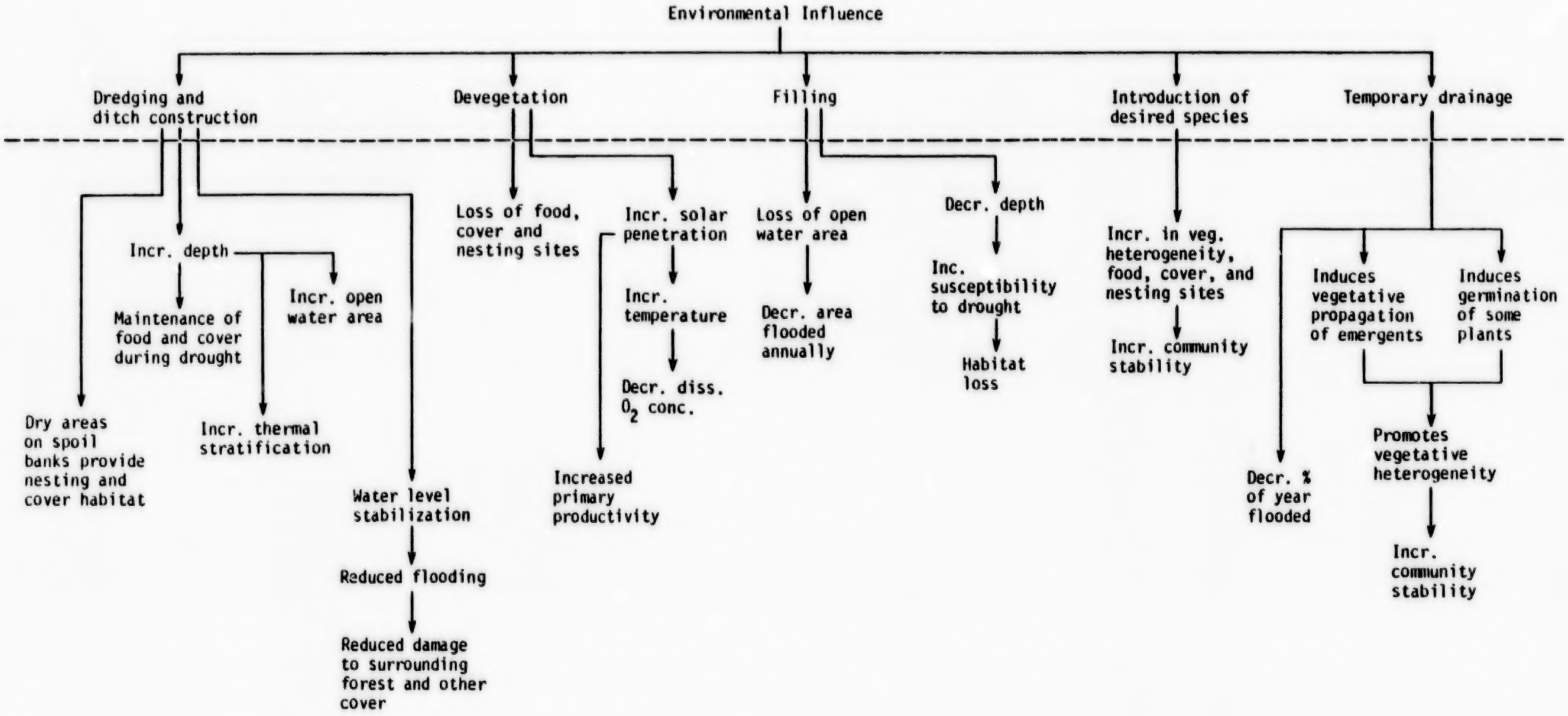
Environmental Influence
Dredging and ditch construction
Devegetation
Filling
Introduction of desired species
Temporary drainage
Dry areas on spoil banks provide nesting and cover habitat
Incr. depth
Maintenance of food and cover during drought
Incr. open water area
Incr. thermal stratification
Water level stabilization
Reduced flooding
Reduced damage to surrounding forest and other cover
Loss of food, cover and nesting sites
Incr. solar penetration
Incr. temperature
Decr. diss. O_2 conc.
Increased primary productivity
Loss of open water area
Decr. area flooded annually
Decr. depth
Inc. susceptibility to drought
Habitat loss
Incr. in veg. heterogeneity, food, cover, and nesting sites
Incr. community stability
Induces vegetative propagation of emergents
Induces germination of some plants
Decr. % of year flooded
Promotes vegetative heterogeneity
Incr. community stability

Figure 3. Potential impacts of diverse land uses on palustrine habitats. Above the dashed line are land-use practices and below are some of their effects on environmental variables and habitat quality.

is best determined by recording presence or absence on a regular basis for several years. The interval between observations and the number of years of data to be averaged are dependent on time and resource availability, currently available records, and the accuracy required. Weekly observations over a 10-year period will obviously provide a better estimate of this parameter than monthly observations over 5 years. Some working definition of "presence of standing water" must be derived that will be applicable to the monitoring project's goals. For example, presence of any standing water within a 10-ha study area, presence of standing water of at least some minimum surface area within the study area, or presence of standing water of at least some minimum depth may meet critera for quantifying this variable.

Percent Open-Water Area

Percent open water is critical in evaluating habitat quality because some species require open water, some require water with emergent vegetation, some require edge habitat between the two, and others use several types of habitat. Percent of habitat area with emergent vegetation provides similar information and may be preferred where this habitat is more important than open water. Yoakum et al. (1980) state that ideal wetland for waterfowl has one-third open water and two-thirds marsh, whereas Allen (1984) proposes that optimum cover conditions for mink in herbaceous wetlands occur when the wetland basin consists of 50% to 75% emergent herbaceous vegetation. Percent open water changes as emergent plant growth within a wetland habitat increases or decreases. Reduced water depth and greater availability of plant nutrients or solar radiation can increase emergent plant growth.

Percent open-water area or water with emergent vegetation can be estimated using aerial photography and a grid overlay as described above. Sometimes the absolute percentage of open-water area is not as important as how open water is distributed. In these cases, an index of edge abundance is more useful. Several measurement methods are available. The line intercept method for edge measurement described by Schuerholz (1974) is inexpensive, easy to learn, and especially useful for large areas, when suitable maps or photos are available. Hays et al. (1981) describe calculation of edge length per unit area of habitat and Patton (1975) presents a diversity index for edge that is similar to the shoreline development factor described for lacustrine habitats.

Forest Cover

Forest cover in palustrine habitats affects allochthonous input of organic matter, provides shade (which influences temperature and primary productivity), and provides habitat for a variety of animals including wood ducks (*Aix sponsa*), squirrels, mink, and beaver (*Castor canadensis*). The presence of trees in an area inundated with water in the western United States generally indicates that the area is only temporarily flooded. Forest cover can be altered by logging or changes in temporal characteristics of flooding that restrict or allow tree growth in an area. Beavers can fell significant acreages of trees (Allen 1983).

Percent forest area can be determined using grid overlays and aerial photographs as discussed above. Many workers quantify canopy closure as a more ecologically relevant description of forest extent (e.g., Allen 1983, 1984). Canopy closure describes the percent of total area that, when viewed from above, is covered by tree foliage, ignoring minor gaps between branches and holes in the center of the plant. Methods for quantifying canopy closure are discussed later.

Vegetative Heterogeneity

Vegetative heterogeneity is a habitat variable that describes plant species diversity. Plant species diversity is often equated with environmental diversity. Monospecific or relatively homogeneous systems are notoriously unstable, ecologically. Also, most animal species require a variety of plant types for food, cover, nesting, and other activities. Vegetative diversity in palustrine systems is most obvious in a gradient forming concentric circles from deep water to shallower water to dry habitats away from standing water (Weller 1978). The density of bird nests in a marsh is correlated with the diversity of plant communities present (Beecher 1942), and waterfowl productivity is greater in heterogeneous wetlands. Species diversity can be quantified simply by counting the number of distinct plant species within a sample plot of a given size. Values are averaged over a number of sample plots and expressed as species per unit area (e.g., ha, m^2, etc.). Krebs (1982) describes a method for calculating community dominance that gives a value between 0 and 100%, lower values indicating heterogeneity.

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LAND-USE IMPACTS AND MONITORING VARIABLES FOR TERRESTRIAL HABITATS

Table 3 identifies variables commonly measured for monitoring terrestrial habitat quality. Most variables used to quantify habitat quality in terrestrial environments pertain to various characteristics of vegetation or topography and may be used in both grasslands and forests. Sampling techniques for estimating these variables may be quite varied, depending on the vegetation type being sampled (Phillips 1959; National Academy of Science-National Research Council 1962; Cook and Bonham 1977; Department of Forest and Wood Sciences 1979; Hays et al. 1981; Chambers and Brown 1983).

Figure 4 illustrates some land-use influences on terrestrial habitat quality.

TERRESTRIAL HABITAT VARIABLES

Topographic Diversity

Topographic diversity is a variable that describes the relative flatness, hilliness, or undulation of a habitat. It includes the configuration of the surface involving relief, elevation, and position of natural and man made features (Schwarz et al. 1976). Some species are typically found in mountainous areas [e.g., mule deer (*Odocoileus hemionus*)], whereas other species are typically found in flatter areas with good topographic diversity [(e.g., pronghorn *Antilocapra americana*)] (Allen et al. 1984). Topographic diversity is primarily altered by bulldozing, both filling and removal, and erosion. Excessive erosion can also increase topographic diversity as can activities such as strip mining. Topographic diversity of an area can be classified by assigning the percent slope within categories as described below (Allen et al. 1984).

Slope

Slope is the slant or incline of the land, measured in degrees from the horizontal, or in percent, and characterized by the direction (exposure or aspect) (Range Term Glossary Committee 1974).

Slope is often important to help characterize habitat for wildlife and to identify problems or potential problems of erosion or instability. The greater the slope, the greater the potential problems of erosion and instability. Many wildlife species, however, prefer habitats with substantial slope and topographic variability for cover, escape routes, and specific life cycle periods. Pronghorn are a possible exception to this, often preferring moderately undulating topography where they can see great distances without obstructions.

One method for quantifying slope involves separation of topography into four categories including: (1) 0 to 2% slope, flat or nearly so; (2) 3% to 8%

Table 3. Commonly measured terrestrial habitat variables.

Abiotic variables	Community variables	Forest cover variables
Topographic diversity	Basal area	Canopy closure
Slope	Species composition	Diameter breast height
Aspect	Species diversity	Vertical stratification
Soil series	Patchiness	Tree canopy volume
Soil type	Edge availability	Tree cavity density
Soil moisture	Successional stage	Snag density
Soil depth	Plant height	
	Litter depth	
	Standing crop biomass	
	Nutrient cycling	

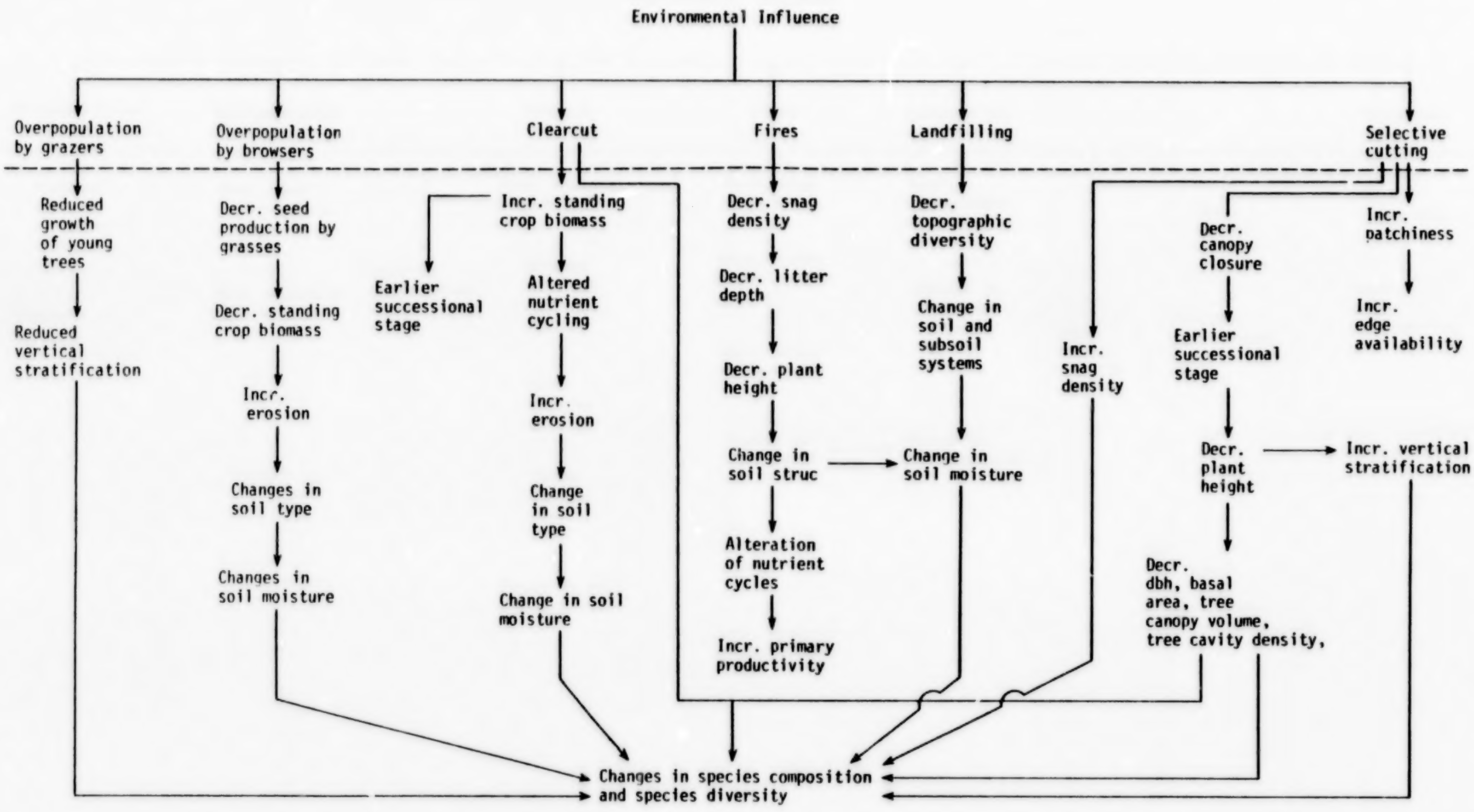
Environmental Influence
Overpopulation by grazers
Overpopulation by browsers
Clearcut
Fires
Landfilling
Selective cutting
Reduced growth of young trees
Reduced vertical stratification
Decr. seed production by grasses
Decr. standing crop biomass
Incr. erosion
Changes in soil type
Changes in soil moisture
Earlier successional stage
Incr. standing crop biomass
Altered nutrient cycling
Incr. erosion
Change in soil type
Change in soil moisture
Decr. snag density
Decr. litter depth
Decr. plant height
Change in soil struc
Alteration of nutrient cycles
Incr. primary productivity
Decr. topographic diversity
Change in soil and subsoil systems
Change in soil moisture
Incr. snag density
Decr. canopy closure
Earlier successional stage
Decr. plant height
Decr. dbh, basal area, tree canopy volume, tree cavity density,
Incr. patchiness
Incr. edge availability
Incr. vertical stratification
Changes in species composition and species diversity

Figure 4. Potential impacts of diverse land uses on terrestrial habitats. Above the dashed line are land-use practices and below are some of their effects on environmental variables and habitat quality.

slope, gently rolling; (3) 9% to 25% slope, substantial drainages, ridges, and/or rims present; and (4) >25% slope, mountainous. Percent slope represents the distance of vertical rise per horizontal run (i.e., 45° angle between level ground and slope = 100% slope). Suggested techniques for quantifying percent slope involve averaging of results obtained from slope and aspect derived from topographic maps, clinometer and compass, or parallax wedge and scale methods described in Hays et al. (1981).

Aspect

Aspect is the predominant direction of the slope of the land (Range Term Glossary Committee 1974). Aspect is important as a habitat variable because some species require certain aspects during some period of the year or during some portion of their life cycle. For example, during the winter bighorn sheep (Ovis canadensis) are often found on south-facing slopes because the slopes are more free of snow and forage is more available than on north-facing slopes. The bighorn sheep will also often loaf or sun themselves on south-facing slopes because of the temperature differences due to the directness of solar radiation. Vegetation growing on south-facing slopes is often more drought tolerant and more sparse than vegetation on other slopes. In the northern hemisphere south facing slopes usually are dryer than other exposures, followed in order of dryness by west-, east-, and north-facing slopes.

Soil Series

Soil classification is a complex but relatively precise field of natural science. Soils are classified in a hierarchical system (analogous to biological taxonomy) that includes the order, suborder, great group, subgroup, family, and series. There are 10 soil orders described in Sopher and Baird (1978). Hodgson (1978) discusses sampling and description techniques for soil classification.

Soil series are the basic unit of soil classification. Soil series is a subdivision of a family and consists of soils that are essentially alike in all major profile characteristics except the texture of the surface (A) horizon (Soil Science Society of America 1973). Knowing the soil series and some of the other hierarchial levels of a soil series can help a person formulate characteristics of the soil important to land-use planning, vegetation growth, and wildlife habitat.

Soil series and its characteristics influence what species and types of vegetation can grow in an area as well as nutrient content of vegetation. Soil series also influences the extent to which erosional and other impacts affect wildlife habitat. Soil series and their characteristics can be altered by siltation due to river flooding, dumping of mine or other waste materials, plowing, removal of topsoil, or soil damage from fires.

Other concepts and characteristics that are helpful in understanding the effects of soils on habitat and environmental planning and impact assessment are noted below.

Soil type

Soil type is the lowest unit in the natural system of soil classification. It is a subdivision of a soil series and consists of described soils that are alike in all characteristics including the texture of the A horizon (Soil Science Society of America 1973).

Soil Texture

Soil texture is based on the relative proportions of the various soil separates in a soil (Soil Science Society of America 1973). The various soil separates include clay, silt, and sand less than 2 mm diameter. Hays et al. (1981) describe a simple test to determine the texture of soil by noting tactile and cohesive qualities. Percentages of silt, sand, and clay can then be used to describe soil type using a triangular diagram (Soil Survey Staff 1975). Soil particle size classes can also be separated by seining through wire-mesh screens of varying sizes. This technique provides more accurate information concerning the relative composition of soils and allows separation of soil particles into more precise size classes. For this method, soil is thoroughly dried and the sample weighed. The sample is then sifted through a series of wire-mesh-bottomed pans with progressively smaller mesh diameters. The weight of soil trapped in each mesh size pan is divided by the total sample weight to obtain percent of that size class in the soil. Table 4 gives soil particle size classes and diameter limits for each as recognized by the Soil Survey Staff (1975).

Soil texture also affects the water-holding capacity and hence the available water for plant growth. The finer the soil texture, the greater the water-holding capacity of the soil.

Soil Moisture

Soil moisture affects wildlife habitat quality primarily because of its influence on the amount and type of vegetation that can grow in habitat. Also, some fossorial animals depend on soil moisture to prevent dessication. Skinks (Eumeces spp.), for example, are found in moist soils, whereas desert iguanas (Dipsosaurus dorsalis) are found in very dry soil areas (Stebbins 1966). Similarly, veery (Catharus fuscescens) are found in areas with moist soils, probably due to the occurrence of dense vegetation (Sousa 1982). One simple system for classification of soil moisture content was proposed by Sousa (1982); it divides forest soils into three categories of spring/early summer conditions: (1) soils typically moist to saturated (e.g., floodplain); (2) soils moderately moist (e.g., upland forest occurring in shaded ravines); and (3) soils typically dry (e.g., upland forest). Soil moisture can also be quantified by obtaining the difference in weight between a soil sample before and after drying. Percentage soil moisture is derived using the following equation (Sopher and Baird 1978).

$$\%\text{ soil moisture} = \frac{\text{weight of soil moisture (i.e., difference between moist and dry soil)}}{\text{dry soil weight}} \times 100$$

Table 4. Sizes of soil separates recognized by the U.S. Department of Agriculture (from Soil Survey Staff 1975).

Soil particle size class	Diameter limits (mm)
Very coarse sand	2.0 to 1.0
Coarse sand	1.0 to 0.5
Medium sand	0.5 to 0.25
Fine sand	0.25 to 0.10
Very fine sand	0.10 to 0.05
Silt	0.05 to 0.002
Clay	<0.002

Hodgson (1978) also discusses classification schemes and techniques for soil moisture regimes. Soil moisture content can be altered by drainage projects, damming, changes in soil composition, land-use changes, management changes, or activities that increase or decrease runoff.

Soil Depth

Soil depth (Foth and Turk 1972) can be important to wildlife species, particularly to those that burrow or spend a portion of their life cycle in a soil or subsurface habitat. Small mammals that may be affected by soil depth include mice, voles, ground squirrels, rats, and gophers. Soil depth affects the water-holding ability of the soil and depth of penetration of plant roots. These in turn affect the species of cover and forage plants that grow on a site.

Basal Area

Basal area is the area of ground surface covered by the stem or stems of a plant. It is usually measured 1 inch above the soil surface, in contrast to the full spread of the foliage. In forestry application, basal area is the area of the cross section at breast height of a single tree or of all the trees in a stand. It is usually expressed in square feet. It may be measured inside or outside the bark, usually the latter (Range Term Glossary Committee 1974).

Basal area is a variable often measured in habitats where soil erosion is a potential problem because of land uses or development. It is important because it is the most direct estimate of the holding capacity of plant infrastructures and roots in preventing soil movement. Basal area is also an important habitat variable because it is indicative of total cover and food availability.

Basal area of woody vegetation is indicative of the volume of wood in an area but, more important to habitat quality considerations, this measure also provides a quantification that considers both the number of trees and tree size in an area. Thus, basal area may be an important indicator of habitat quality for animals that rely on trees for some life requisite. For example, downy woodpeckers (Picoides pubescens) feed on insects found on trees. Therefore, basal area within a forest habitat may indicate prey availability for this species (Schroeder 1982c). Basal area, like diameter breast height, can be affected by cutting, or change over time as a stand of trees grows. Basal area is calculated by obtaining the diameters of trees in a stand. Basal area of each tree can then be determined by assuming that the cross section of each tree forms a circle and using the formula:

$$A = \frac{\pi D^2}{4} = 0.785 D^2$$

where A = area (in square of units of D)

D = diameter (length)

Basal areas of all trees within the sample area are added together to obtain basal area per unit area (Hays et al. 1981).

Species Composition

Species composition describes the proportions of various plant species in relation to the total vegetation on a given area. It may be expressed in terms of cover, density, weight, or frequency (Range Term Glossary Committee 1974). Species composition may also refer to the proportions of various animal species in relation to the total animal population on a given area.

Vegetative species composition of the habitat is important in determining habitat quality. Each wildlife species has its own requirements for this parameter and knowledge of these requirements is necessary to devise a sampling strategy. For example, southern red-backed voles (Clethrionomys gapperi) require grasses or sedges (Caryx spp.) (Allen 1983b), Lewis' woodpecker (Melanerpes lewis) requires mast-producing shrubs and trees (Sousa 1983b), sage grouse (Centrocercus vrophasianus) require sage (Artemisia tridentata) (Boyce 1981), Williamson's sapsucker (Sphyrapicus thyroideus) prefers some aspen (Populus tremuloides) (Sousa 1983a), the pine warbler (Dendroica pinus) requires pines (Pinus spp.) (Schroeder 1982a), and martens (Martes americana) require fir (Abies lasiocarpa, Pseudotsuga menziesii) or spruce (Picea engelmannii).

Species composition of a community can be altered by changes in habitat quality or by introduction or removal of species. Normally, when species composition is quantified, only species of vegetation are considered because of the relative ease with which parameters in plant species composition can be obtained. Species composition may be quantified as presence or absence of a particular species, percent canopy coverage of the important species, density of the species, dominant species biomass, or other parameters. Methods for sampling species composition are cited in Phillips (1959), National Academy of Sciences-National Research Council (1962), Cook and Bonham (1977), Hays et al. (1981), and Chambers and Brown (1983).

Species Diversity

Species diversity is the number of species occurring in some location or under some set of conditions (Schwarz et al. 1976). In its simplest application, the number of species present represents species diversity; however, numerous other species diversity indices are often used (Odum 1971). Species diversity is usually quantified as species of some type (e.g., herbs, mast producing trees, insects) per unit area or cover type. Sometimes the restriction is added that each species must make up some percentage of the biomass, abundance, or canopy area to be counted.

Species diversity is often important in determining habitat quality for an area because most wildlife species require numerous food and cover types and high species diversity often indicates a stable community with much edge habitat. Multiple species composition can also provide a wider temporal and nutritive availability of food supply. For example, gray squirrel (Sciurus griseus) habitat is assumed to be optimal when at least four species of hard-mast-producing trees are present (Allen 1982). Similarly, blue grouse (Dendragapus obscurus) habitat is best when vegetation is diverse because this provides both diverse vegetative food and diverse insect food that inhabits such vegetation (Schroeder 1984). Species diversity is often equated with environmental heterogeneity. Vegetative species diversity can be affected by altering topographic and soil characteristics, drainage patterns, agricultural practices, and any species propagation or removal.

Patchiness

Patchiness is another variable that measures heterogeneity within potential habitat. Patchiness was used by Boyce (1981) in assessing sage grouse habitat quality and was defined as being equal to the number of times a belt transect (2 m x 1,000 m) crossed from one habitat type to another, plus 1.0. For field implementation of this variable, habitat types need to be defined for each application. Patchiness is a function of the spatial frequency of environmental heterogeneity, which in turn is affected by the spatial frequency of changes in topography, soil, drainage, and human influences.

Edge Availability

Edge availability is likewise a function of environmental heterogeneity. It reflects the common boundaries between habitat types within an area. Sometimes these edges are called ecotones (Odum 1971). Edge, however, is more than an interface; it describes a type of habitat in and of itself that is heavily utilized by a variety of species. Patton's (1975) diversity index, which is most commonly used to described edge, relates the linear extent of a measured edge (TP) of a habitat to the perimeter of a circle with area (A) equal to that of the habitat according to the formula:

$$DI = \frac{TP}{2\sqrt{A\pi}}$$

where DI = diversity index

TP = measured edge between habitats

A = area of habitats in sampling block

$\sqrt{\ }$ = root, example $2\sqrt{\ }$ = square root

π = 3.14 (the ratio of the length of the circumference of a circle to its diameter)

Allen (1984b) used a variation of this method. Additionally, Patton's diversity index is often supplemented by suffixing the number of habitat types and size of the habitat [e.g., 1.85(3)100 indicates a habitat of 100 ha with three habitat types and a diversity index of 1.85]. Edge may also be measured directly by tape measure, pacing, or aerial photography (Hays et al. 1981). Measurement of edge by the line intercept method was discussed by Schuerholz (1974) who considered this method more suitable than others for use with aerial photographs or in the field.

Successional Stage

Succession is an orderly process of community development that involves changes in species structure, abundance, and function over time. It results from modification of the physical environment by the community even though the physical environment determines the pattern and rate of changes. It often culminates in a stabilized ecosystem called climax. The sequence of communities is called the sere and the transitory communities are called seral, successional, developmental, or pioneer stages (Odum 1971).

Successional stage of a community is most often thought of with regard to forest habitats, however, any habitat type can pass through various successional stages. For example, in many grassland habitats, grasses represent a climax community. Overgrazing or other perturbations set back the successional process, often resulting in the invasion of woody plants. The result of this process is often termed a disclimax. In forested mountain areas, aspen (*Populus* spp.) are often early successional species and are replaced in later stages by fir (*Abies* spp.), spruce (*Picea* spp.), pine, or other trees. One method of quantifying successional stage, and the most frequently used, is classification by dominant plant species or type. For a forest community, such a method might use six categories arranged from earliest to latest stage including: (1) grass-forb, (2) shrub-seedling, (3) pole-sapling, (4) young trees, (5) mature trees, and (6) old growth (Allen 1984a). These categories, however, are largely subjective and precise definitions for each would be required before the method could be accurately employed. While successional stage of a community, by definition, advances over time, successional stage is virtually always set back by land-use practices. Perturbations such as burning, logging, mowing, grazing, or others create such an effect. For some species, a disclimax or earlier successional habitat is preferable for species management as compared to a climax habitat. Successional stage of an area affects wildlife habitat quality. Pine warblers (Schroeder 1982a) and marten (Allen 1984a) prefer mature forests, whereas ruffed grouse (Bonasa umbellus) and white-tailed deer (Odocoileus virginianus) prefer early successional forest.

Plant Height

Plant height can describe many different habitat characteristics depending on how the variable is defined. For example, plant height can measure average height of herbaceous plants, shrubs, or trees, or percent of such vegetation type above or below some height. Also, heights of various vertical strata in a habitat or maximum heights of some vegetation type might be measured. Vegetational height can affect such habitat aspects as forage availability in winter, primary productivity, cover quality, and nesting sites. Vegetation height can be measured directly using yardsticks or a graduated rod if the plant height is within the limits of this technique. Hays et al. (1981) describe merrit hypsometer, christen hypsometer, trigonometric hypsometry, graduated rod, optical range finder, parallax wedge, and parallax bar methods for determination of plant height.

Litter Depth

Litter depth describes the amount of dead plant material and partially decomposed organic material that have accumulated on the soil surface. Litter reduces soil dessication rate and provides a microhabitat in which many vertebrates and invertebrates can live. Deep litter can prevent growth of certain species. For example, climax stages of grass on midwestern prairies prior to agricultural alterations were characterized by a very thick sod covering. This sod was composed of grass-derived organic debris and prevented the establishment of woody vegetation. Similarly, leaf litter in forests can prevent growth of herbaceous plants. Litter depth can be altered by impacts such as fires, plowing, and cutting of standing vegetation. Hays et al. (1981) suggest averaging of measurements taken with a graduated rod to quantify litter depth.

Standing Crop Biomass

Primary productivity describes the amount of vegetation produced in a given time per unit area. Primary productivity can be affected by changes in nutrient content of the soil (fertilization and depletion), erosion, grazing intensity, seeding, removal of competition, and water availability. Brown

(1954) and Campbell (1969) identify several methods available for quantification of primary productivity; however, these do not estimate primary productivity, but rather standing crop biomass. Primary productivity is a difficult and expensive variable to measure or estimate and therefore, is rarely used in research or environmental monitoring. In most cases, standing crop biomass is used as an indicator of primary productivity, with satisfactory results. It is best to average estimates of standing crop within several sample plots and to extrapolate data obtained to the general area. The most accurate estimates are obtained by cutting and weighing plants on a plot, although methods involving condition of the range, condition of grazing animals, ocular estimation, and twig length and volume of shrubs are available as well. Major impacts on grasslands (Figure 4) include those associated with overgrazing and controlled burns.

Nutrient Cycling

Nutrients are important to animal and plant life in both aquatic and terrestrial ecosystems. Chemical elements tend to circulate in the biosphere in characteristic paths from environment to organisms and back to the environment. Movement of these elements and inorganic compounds, which are essential to life, is called nutrient cycling (Odum 1971). The nutrient cycles most commonly monitored are nitrogen (N), phosphorus (P), potassium (K), and sulfur (S). For each elemental cycle, such as N or S, it is helpful to identify two pools: (1) the reservoir pool, which is the large, slow-moving nonbiological component; and (2) the exchange or cycling pool, which is a smaller more active portion of the cycle where rapid exchanges are occurring between organisms and their environment (O'Neill et al. 1975).

This cycling affects habitat variables. Most management and development activities increase the rate of change from the reservoir pool to the exchange pool. In cases such as N and P cycles, these disturbances may shift the losses of N and P from terrestrial to aquatic habitats. This change in the aquatic communities results in decreased oxygen and an increase in species more adapted to the higher nutrient content of the aquatic system (Smith 1980).

Other concepts that are important in nutrient cycling and biogeochemical processes are turnover rates, decomposition rates, and mineral weathering rates (Howell et al. 1975).

Canopy Closure

Canopy closure is perhaps the most commonly employed means of quantifying habitat quality parameters. Canopy closure is the portion of ground area covered by the vertical projection downward of the aerial portions of plants. It is usually expressed as a percentage of the total area within the habitat. The term is most often used in vegetation communities dominated by shrubs and trees. Schroeder (1982b) defined canopy closure as the percent of the ground surface that is shaded by a vertical projection of the canopies of whatever vegetative type is of importance. Cover or ground cover are terms often used to express a similar concept as canopy closure. Cover and ground cover are terms usually used to describe herbaceous, and low-growing shrub community types. Canopy closure of many different vegetational components can be measured. For example, percent canopy closure can be determined for all trees (Allen 1983a, 1984b), trees that produce hard mast (Allen 1982), trees of specific types (Allen 1984a; Schroeder 1982a, 1984; Sousa 1983a,b), herbaceous cover (Schroeder 1984; Sousa 1982, 1983b), and grass cover (Allen 1983b; Sousa 1983c). Canopy closure is often used when there is variability in the area covered by an individual plant and abundance of a vegetative type is important, or if it is not feasible to count individual plants. The extent of canopy closure is altered by anything that alters the growth and maintenance of plant communities. Examples of these include the effects of solar radiation, soil nutrients, soil moisture, fires, grazing, browsing, pest infestations, cutting, and other disturbances. Numerous techniques for estimation of canopy closure are covered in Hays et al. (1981) and include line intercept, Bitterlich method, calculated cover, step point, pin frame, spherical densiometer, canopy cover, and ocular estimation of cover. Suggestions for selecting the appropriate method for different situations are included also.

Diameter Breast Height

Diameter breast height (dbh) is a measurement of a tree's diameter at breast height. Because breast height varies among individuals, it has been standardized as 1.4 m (4.5 ft) above ground level. Suggested methods for obtaining dbh measurements are a diameter tape or a Biltmore stick (Hays et al. 1981). Diameter breast height measurements can be used in a number of ways to describe habitat variables. Variables might be defined as percentage of trees above or below some dbh size, percentage between specified sizes, average dbh, average dbh of trees of some type (e.g., hard-mast-producing, deciduous, overstory), average dbh of snags, or number of trees per unit area within some dbh class. Diameter breast height is correlated with height and age of trees and, hence, dbh indicates the presence of trees of a particular age class. Different species utilize trees and tree stands of specific ages because of cover, food, or nesting-site availability. Therefore, dbh information is useful in determining habitat quality. Diameter breast height characteristics of a forest habitat can change because of tree-cutting or fires, or over time as trees grow and mature.

Vertical Stratification

Vertical stratification describes the diversity of tree sizes and understory/overstory layers. Forests with little vertical stratification are usually composed of single-age-classes of trees and provide little habitat diversity. These stands of trees are especially susceptible to natural environmental perturbations such as pests, parasites, and disease. Greater vertical stratification provides greater niche diversity and, greater species diversity. Allen (1983a) suggests a classification scheme consisting of three categories for quantifying vertical stratification in potential fisher (Martes pennanti) habitat: (1) single-storied: stand canopy is composed of dominant and codominant trees that are generally of the same age and size class; canopies of the trees are within the same height stratum, or are overlapping; understory trees compose less than 10% of canopy closure; (2) two-storied: stand canopy is stratified into two distinct layers, overstory and understory; the understory is clearly developed, having more than 10% canopy closure of trees with their crowns entirely below the dominant canopy strata; and

(3) multi-storied: stand canopy is composed of the crowns of trees in various age and size classes; shrub trees of intermediate height, dominant, and codominant trees all occur in the stand. Foliage height diversity can also be quantified using the Shannon-Weiner index (Hays et al. 1981; MacArthur and MacArthur 1961). Vertical stratification can be altered by thinning of large trees to produce more unshaded areas where younger trees can grow.

Tree Canopy Volume

Tree canopy volume is the three-dimensional space occupied by the living foliage of a tree. Because many species and their prey live within the tree canopy this variable can influence habitat quality [e.g., black-capped chickadee, Parus atricapillus (Schroeder 1982d)]. Sturman (1968) developed methods for quantifying canopy volume for both coniferous and deciduous species. Canopy volume is determined for individual trees. These values can be added to determine canopy volume per unit area of forest habitat Tree canopy volume may be affected by pest-caused defoliation, drought, fires, cutting of trees, solar penetration, and other natural and human-related impacts.

Tree Cavity Density

Tree cavity density is important to habitat quality because of the nesting, hibernation, and cover habitat that tree cavities provide to a variety of species. For example, wood duck (Aix sponsa) breeding habitat quality is assumed to be dependent in part on the availability of suitable tree cavities (Sousa and Farmer 1983). Tree swallows (Iridoprocne bicolor), black-capped chickadees, and many species of woodpeckers (Piciformes) nest in tree cavities as well. Estimates of tree cavity density are best made by visual observation and counting. Density is usually reported as tree cavities per unit or hectare. Tree cavity density can be increased by boring holes in the trunks and allowing natural cavity producers (e.g., woodpeckers) to modify these to suit species requirements. Tree cavities are often found in dead trees, so increasing the number of snags by girdling living trees can also increase tree cavity density. Alternatively, nest boxes may be erected, which provide the same nesting, hibernating, or cover habitat.

Snag Density

Snag density describes the number of standing dead trees per unit area in a forest habitat. Many animals live and nest in cavities within snags, and snags provide habitat for many invertebrates that serve as a food source for other animals (Schroeder 1982b). Snag density is best quantified by marking out sample plots and visually identifying and counting the number of snags. Often, only snags within some size class are counted because only these provide the pertinent life requisite. Snag density may be decreased by cutting (especially for firewood collection), fires, or wind storms and may be increased by insect or disease infestations or girdling by animals or humans. Girdling involves removal of the outer layer of living tissue of trees in a complete circle around the tree. This interrupts the flow of water and nutrients within the tree and causes its death. Major impacts on forested lands (Figure 4) include those associated with controlled burns, clear cutting, and selective cutting.

Table 5 is a matrix relating habitat variables discussed in this chapter and land-use practices that can affect each. Variations in habitat quality are, of course, much more complex than are presented here. Most habitat variables covary with one another and influences are interrelated. Because of this, virtually every land use listed in the table can in some way affect each environmental variable. This table summarizes of the most common and direct influences.

Table 5. Summary table of terrestrial variables discussed and land-use practices that may affect each variable.

Variables	Actions Affecting Terrestrial Variables														
Terrestrial	Construction projects	Dredging	Waste discharges	Impoundments	Industrial/municipal water consumption	Irrigation	Drainage	Erosion	Livestock grazing	Acid rain	Vegetation removal	Water velocity changes	Solar penetration	Species introductions	Fires	Floods
Topographic diversity	X							X	X		X					X
Slope	X			X				X								
Aspect				X												
Soil series	X						X									X
Soil type	X	X				X	X	X	X		X			X	X	X
Soil moisture	X	X				X	X	X			X			X	X	X
Soil depth	X							X				X				X
Basal area	X								X		X		X	X	X	
Species composition	X					X		X	X		X		X	X	X	X
Species diversity	X					X		X	X		X		X	X	X	X
Patchiness	X					X		X	X		X			X	X	X
Edge availability	X					X		X	X		X			X	X	X
Successional stage	X							X	X		X			X	X	X
Plant height	X					X	X		X		X		X	X	X	X
Litter depth	X								X		X			X	X	
Standing crop biomass	X					X	X	X	X		X		X	X	X	X
Nutrient cycling	X	X	X	X			X	X	X	X	X		X	X	X	X
Canopy closure	X					X			X		X			X	X	X
Diameter breast high	X								X		X		X	X	X	
Vertical stratification	X								X		X		X	X	X	
Tree canopy volume	X								X		X		X	X	X	
Tree cavity density	X								X		X		X	X	X	X
Snag density	X								X		X		X	X	X	X

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GLOSSARY

allochthonous - From outside of the system. In the context of this publication, it refers to organic material of terrestrial origin that falls or is washed into an aquatic system.

area flooded annually - The average maximum area of land that is covered by standing water at some time during the year.

aspect - The predominant direction of slope of the land surface.

basal area - The horizontal cross sectional area through a tree trunk or the area of ground surface covered by the stem or stems of herbaceous plants.

benthos - The animal and plant life that inhabit the bottom of an aquatic habitat.

biochemical oxygen demand (BOD) - A measure of the demand on a water body's dissolved oxygen supply over a given period of time due to biological decomposition of organic material.

canopy closure - The vertical projection downward of the aerial portions of plants, usually expressed as a percentage of the total area. Somewhat synonymous terms are cover and ground cover.

diameter breast height (dbh) - A tree's diameter at breast height (4.5 ft) above ground level.

dimictic - Lakes in which circulation occurs each spring and autumn in response to temperatures.

edge availability - A function of environmental heterogeneity, it is an estimate of the edge or common boundaries between habitat types within an area.

electrical conductivity - The ability of a substance to allow free electrons to move through it.

environmental variable - A habitat variable that exists at numerous levels and whose various levels correlate with the quality of the habitat.

estuarine - Areas where freshwater meets and mixes with salt water. Estuaries typically occur at the mouths of rivers, bays, lagoons, and salt marshes.

eutrophic - An aquatic system that is very rich in organic nutrients and has high vegetative biomass.

guild - A group of organisms having similar habitat requirements.

Habitat Suitability Index (HSI) models - A system of qualitative and quantitative representations of the ability of environments to support populations of specific species. Habitat Suitability Index models are a part of the Habitat Evaluation Procedures developed by the U.S. Fish and Wildlife Service.

lacustrine - Standing freshwater bodies of water (e.g., lakes).

lentic - Standing water.

lotic - Moving water.

mesotrophic - Aquatic environments that are somewhere between eutrophic and oligotrophic with regard to nutrient and vegetative biomass content.

model - A representation or abstraction of a real system; an attempt to present a simplification of a system in terms of a few of its relevant variables.

nanoplankton - Floating organisms that pass through a 63 µ mesh net.

oligotrophic - Bodies of water that have low nutrient content and little vegetative biomass. Oligotrophic waters are usually cold, deep, and clear.

palustrine - Concerning highly productive natural environments that are permanently or seasonally inundated with shallow water.

patchiness - An estimate of the heterogeneity of habitat types within an area.

pelagic - Open-water areas beyond the littoral zone.

phytoplankton - Photosynthetic, free-floating organisms.

pioneer stage - One of the earliest successional stages.

pool/riffle ratio - The area of a lotic habitat that is composed of pools, divided by the area of the habitat that is composed of riffles.

pools - Areas of a lotic water body that are deeper and of lower current velocity than the main current.

protists - Aquatic organisms that include the bacteria and the flagellates.

riffles - Areas of a lotic water body that are shallower and of higher current velocity than the main current. Riffles usually have a broken water surface.

riverine - Pertaining to rivers or permanently flowing bodies of water.

salinity - The total solids in water after all carbonates have been converted to oxides, all bromides and iodides have been replaced by chlorides and all organic matter has been oxidized (i.e., the salt content of water).

seral stage - See successional stage.

sere - The sequence of communities leading to a climax community.

sinuosity - The degree to which a lotic water body deviates from straightness.

slope - The slant or incline of the land surface, measured in degrees from the horizontal, or in percent, or expressed as a vertical:horizontal ratio.

snag density - The number of snags (standing dead trees) per unit area.

soil depth - The vertical distance from the soil surface to the level at which soil weathering has been effective or to the level of root penetration or both.

soil moisture - Water contained in the soil.

soil series - The basic unit of soil classification; a subdivision of a family, which consists of soils that are essentially alike in all major profile characteristics except the texture of the surface (A) horizon.

soil texture - The relative proportions of the various soil separates (e.g, sand, silt, clay) in a soil.

soil type - A subdivision of a soil series, which consists of described soils that are alike in all characteristics including the texture of the surface (A) horizon.

species composition - The proportion of various plant or animal species in relation to the total vegetation or total animal population, respectively, on a given area.

species diversity - The number of species occurring in some location or under some set of conditions.

standing crop biomass - The total amount of living plant material, in above ground parts, per unit of space at a given time.

successional stage - One of a sequence of communities in the seral development leading to a climax community.

surface (A) horizon - The soil horizon of maximum biological activity, which is subject to the most direct influences of climate, plants, animals and other forces in the environment.

thermal stratification - Abrupt vertical demarcations between water layers of differing temperatures.

total dissolved solids (TDS) - The aggregate of carbonates, bicarbonates, chlorides, sulfates, phosphates, nitrates, and other salts of calcium, magnesium, sodium, potassium, and other substances.

trophic class - The state of an aquatic environment with regard to eutrophication.

turbidity - The extent to which light is scattered by suspended or colloidal material as it passes through a column of water.

tree canopy volume - The three-dimensional space occupied by the living foliage of a tree.

tree cavity density - The number of tree cavities per unit area.

turnover rate - The quantity of a substance in a system divided by the time required for that quantity to move through the system.

vertical stratification - The diversity of tree sizes and understory/overstory layers.

zooplankton - Nonphotosynthetic, free-floating organisms.

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B. M. Graves[1] and P. L. Dittberner[2]

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

[1]Dept. of Zoology & Physiology
University of Wyoming
Laramie, WY 82071

[2]Natural Resource Professionals
1616 Independence Court
Ft. Collins, CO 80526

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This manual provides general conceptual guidelines for designing habitat monitoring projects and identifying key variables that may indicate habitat quality. References are provided that lead to more detailed discussions of important topics. The field of habitat monitoring is quite broad and appropriate field methods may vary from site-to-site. Hence, this manual cannot provide a step-by-step procedure for habitat monitoring. Rather, it provides a framework and general principles; designers of individual monitoring programs must integrate and adapt these to fit specific circumstances.

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Use Natural Resources Wisely

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U.S. FISH AND WILDLIFE SERVICE

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

END

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